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CMS Collaboration ; Khachatryan, V ; Amsler, C ; Chiochia, V

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Dijet Azimuthal Decorrelations in pp Collisions at $\sqrt{s} = 7$ TeV

The CMS Collaboration*

Abstract

Measurements of dijet azimuthal decorrelations in pp collisions at $\sqrt{s} = 7$ TeV using the CMS detector at the CERN LHC are presented. The analysis is based on an inclusive dijet event sample corresponding to an integrated luminosity of 2.9 pb^{-1} . The results are compared to predictions from perturbative QCD calculations and various Monte Carlo event generators. The dijet azimuthal distributions are found to be sensitive to initial-state gluon radiation.

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*See Appendix A for the list of collaboration members

High-energy proton-proton collisions with high momentum transfer are described within the framework of Quantum Chromodynamics (QCD) as point-like scatterings between the proton constituents, collectively referred to as partons. The outgoing partons manifest themselves, through quark and gluon soft radiation and hadronization processes, as localized streams of particles, identified as jets. At Born level, dijets are produced with equal transverse momenta p_T with respect to the beam axis and back-to-back in the azimuthal angle ($\Delta\varphi_{\text{dijet}} = |\varphi_{\text{jet1}} - \varphi_{\text{jet2}}| = \pi$). Soft-gluon emission will decorrelate the two highest p_T (leading) jets and cause small deviations from π . Larger decorrelations from π occur in the case of hard multijet production. Three-jet topologies dominate the region of $2\pi/3 < \Delta\varphi_{\text{dijet}} < \pi$, whereas angles smaller than $2\pi/3$ are populated by four-jet events.

Dijet azimuthal decorrelations, i.e., the deviation of $\Delta\varphi_{\text{dijet}}$ from π for the two leading jets in hard-scattering events can be used to study QCD radiation effects over a wide range of jet multiplicities without the need to measure all the additional jets. Such studies are important because an accurate description of multiple-parton radiation is still lacking in perturbative QCD (pQCD). Experiments therefore rely on Monte Carlo (MC) event generators to take these higher-order processes into account in searches for new physics and for a wide variety of precision measurements. The observable chosen to study the radiation effects is the differential dijet cross section in $\Delta\varphi_{\text{dijet}}$, normalized by the dijet cross section integrated over the entire $\Delta\varphi_{\text{dijet}}$ phase space, $(1/\sigma_{\text{dijet}})(d\sigma_{\text{dijet}}/d\Delta\varphi_{\text{dijet}})$. By normalizing the $\Delta\varphi_{\text{dijet}}$ distributions in this manner, many experimental and theoretical uncertainties are significantly reduced. Measurements of dijet azimuthal decorrelations at the Tevatron have previously been reported by the D0 collaboration [1]. In this Letter, we present the first measurements of dijet azimuthal decorrelations in pp collisions at $\sqrt{s} = 7$ TeV at the CERN Large Hadron Collider (LHC).

The central feature of the Compact Muon Solenoid (CMS) apparatus is a superconducting solenoid, of 6 m internal diameter, providing an axial field of 3.8 T. Charged particle trajectories are measured by the silicon pixel and strip tracker, covering $0 < \varphi < 2\pi$ in azimuth and $|\eta| < 2.5$, where pseudorapidity $\eta = -\ln[\tan(\theta/2)]$ and θ is the polar angle relative to the counterclockwise proton beam direction with respect to the center of the detector. A lead-tungstate crystal electromagnetic calorimeter and a brass/scintillator hadronic calorimeter surround the tracking volume. The calorimeter cells are grouped in projective towers of granularity $\Delta\eta \times \Delta\varphi = 0.087 \times 0.087$ at central pseudorapidities. The granularity becomes coarser at forward pseudorapidities. A preshower detector made of silicon sensor planes and lead absorbers is installed in front of the electromagnetic calorimeter at $1.653 < |\eta| < 2.6$. Muons are measured in gas-ionization detectors embedded in the steel magnetic field return yoke. A detailed description of the CMS detector can be found elsewhere [2].

CMS uses a two-tiered trigger system to select events online; Level-1 (L1) and the High Level Trigger (HLT). In this analysis, events were selected using two inclusive single-jet triggers that required an L1 jet with $p_T > 20$ GeV (30 GeV) and an HLT jet with $p_T > 30$ GeV (50 GeV). The jets at L1 and HLT are reconstructed using energies measured by the electromagnetic and hadronic calorimeters and are not corrected for the jet energy response of the calorimeters. The trigger efficiency for a given corrected p_T threshold of the leading jet (p_T^{max}) was measured using events selected by a lower-threshold trigger. For the event selection, p_T^{max} thresholds were chosen so that this efficiency exceeded 99%. The corresponding offline corrected p_T^{max} values are 80 GeV (110 GeV) for the low (high) threshold jet trigger.

Jets were reconstructed offline using the anti- k_T clustering algorithm with a distance parameter $R = 0.5$ [3]. The four-vectors of particles reconstructed by the CMS particle-flow algorithm were used as input to the jet-clustering algorithm. The particle-flow algorithm combines in-

formation from all CMS sub-detectors to provide a complete list of long-lived particles in the event. Muons, electrons, photons, and charged and neutral hadrons are reconstructed individually. As a result, the residual corrections to the jet four-vectors, arising from the detector response, are relatively small (at the level of 5-10% in the central region) [4]. A detailed description of the particle-flow algorithm can be found elsewhere [5, 6].

Spurious jets from noise and non-collision backgrounds were eliminated by applying loose quality cuts on the jet properties [7]. Events were required to have a primary vertex reconstructed along the beam axis and within 24 cm of the detector center [8]. Further cuts were applied to reject interactions from the beam halo. Events were selected having two leading jets each with $p_T > 30$ GeV and rapidity $|y| < 1.1$, where $y = \frac{1}{2} \ln[(E + p_z) / (E - p_z)]$, with E being the total jet energy and p_z the projection of the jet momentum along the beam axis. Each event is put into one of five mutually exclusive regions, which are based on the p_T^{\max} in the event. The five regions are: $80 < p_T^{\max} < 110$ GeV, $110 < p_T^{\max} < 140$ GeV, $140 < p_T^{\max} < 200$ GeV, $200 < p_T^{\max} < 300$ GeV, and $300 \text{ GeV} < p_T^{\max}$. The data correspond to an integrated luminosity of 0.3 pb^{-1} for the lowest p_T^{\max} region and 2.9 pb^{-1} for the other p_T^{\max} regions. The uncertainty on the integrated luminosity is estimated to be 11% [9]. After the application of all selection criteria, the numbers of events remaining in each of the five p_T^{\max} regions, starting from the lowest, are: 60837, 160388, 69009, 14383, and 2284.

The $\Delta\phi_{\text{dijet}}$ distributions are corrected for event migration effects due to the finite jet p_T and position resolutions of the detector. The distributions are sensitive to the jet p_T resolution because fluctuations in the jet response can cause low-energy jets to be misidentified as leading jets, and events can migrate between different p_T^{\max} regions. The finite resolution in azimuthal angle causes event migration between $\Delta\phi_{\text{dijet}}$ bins, while the resolution in rapidity can move jets in and out of the central rapidity region ($|y| < 1.1$). The correction factors were determined using two independent MC samples: PYTHIA 6.422 (PYTHIA6) [10] tune D6T [11], and HERWIG++ 2.4.2 [12]. The p_T , rapidity, and azimuthal angle of each generated jet were smeared according to the measured resolutions [13]. The ratio of the two dijet azimuthal distributions (the generated distribution and the smeared one) determined the unfolding correction factors for each p_T^{\max} region, for a given MC sample. The average of the correction factors for each p_T^{\max} region from the two MC samples were used as the final unfolding correction applied to data. The unfolding correction factors modify the measured $\Delta\phi_{\text{dijet}}$ distributions by less than 2% for $5\pi/6 < \Delta\phi_{\text{dijet}} < \pi$. For $\Delta\phi_{\text{dijet}} \sim \pi/2$, the changes range from -11% , for the highest p_T^{\max} region, to -19% , for the lowest.

The main sources of systematic uncertainty arise from uncertainties in the jet energy calibration, the jet p_T resolution, and the unfolding correction. The jet energy calibration uncertainties have been tabulated for the considered phase space in the variables of jet p_T and η [4]. Typical values are between 2.5% and 3.5%. The resulting uncertainties on the $\Delta\phi_{\text{dijet}}$ distributions range from 5% at $\Delta\phi_{\text{dijet}} \sim \pi/2$ to 1% at $\Delta\phi_{\text{dijet}} \sim \pi$. The effect of jet p_T resolution uncertainty on the $\Delta\phi_{\text{dijet}}$ distributions was estimated by varying the jet p_T resolutions by $\pm 10\%$ [13] and comparing the $\Delta\phi_{\text{dijet}}$ unfolding correction before and after the change. This yields a variation on the normalized $\Delta\phi_{\text{dijet}}$ distributions ranging from 5% at $\Delta\phi_{\text{dijet}} \sim \pi/2$ to 1% at $\Delta\phi_{\text{dijet}} \sim \pi$. The uncertainties on the unfolding correction factors were estimated by comparing the corrections from different event generators and PYTHIA6 tunes that vary significantly in their modelling of the jet kinematic distributions and $\Delta\phi_{\text{dijet}}$ distributions. The resulting uncertainty varies from 8% at $\Delta\phi_{\text{dijet}} \sim \pi/2$ to 1.5% at $\Delta\phi_{\text{dijet}} \sim \pi$. The systematic uncertainty from using a parametrized model to simulate the finite jet p_T and position resolutions of the detector to determine the unfolding correction factors was estimated to be about 2.5% in all p_T^{\max} regions. The combined systematic uncertainty, calculated as the quadratic sum of all systematic uncer-

tainties, varies from 11% at $\Delta\phi_{\text{dijet}} \sim \pi/2$ to 3% at $\Delta\phi_{\text{dijet}} \sim \pi$.

The corrected differential $\Delta\phi_{\text{dijet}}$ distributions, normalized to the integrated dijet cross section, are shown in Fig. 1 for the five p_T^{max} regions. The distributions are scaled by multiplicative factors for presentation purposes. Each data point is plotted at the abscissa value for which the predicted differential $\Delta\phi_{\text{dijet}}$ distribution has the same value as the bin average obtained using PYTHIA6 tune D6T, which provides a good description of the data [14].

The $\Delta\phi_{\text{dijet}}$ distributions are strongly peaked at π and become steeper with increasing p_T^{max} . The simulated $\Delta\phi_{\text{dijet}}$ distributions from the PYTHIA6 (D6T and Z2 [15] tunes), PYTHIA 8.135 (PYTHIA8) [16], HERWIG++, and MADGRAPH 4.4.32 [17] event generators are presented for comparison. The MADGRAPH generator is based on leading-order matrix element multiparton final-state predictions, using PYTHIA6 for parton showering and hadronization, and the MLM method [18] to map the parton-level event into a parton shower history. The MADGRAPH predictions included tree-level processes of up to four partons. For PYTHIA6, PYTHIA8, and MADGRAPH event generators the CTEQ6L [19] parton distribution functions (PDFs) were used; for HERWIG++, the MRST2001 PDFs [20].

Figure 2 shows the ratios of the measured $\Delta\phi_{\text{dijet}}$ distributions to the predictions of PYTHIA6, PYTHIA8, HERWIG++, and MADGRAPH in the five p_T^{max} regions. The combined systematic uncertainty on the experimental measurements is shown by the shaded band. The predictions from PYTHIA6 and HERWIG++ describe the shape of the data distributions well, while MADGRAPH (PYTHIA8) predicts less (more) azimuthal decorrelation than is observed in the data.

Figure 3 displays a comparison between the measured $\Delta\phi_{\text{dijet}}$ distributions and the predictions of pQCD calculations from the parton-level generator NLOJET++ [21] within the FASTNLO framework [22]. The predictions near $\Delta\phi_{\text{dijet}} = \pi$ have been excluded because of their sensitivity to higher-order corrections not included in the present calculations. The leading-order (LO) curves represent processes with three partons in the final state, normalized to the LO σ_{dijet} ($2 \rightarrow 2$) cross section. The next-to-leading-order (NLO) predictions include $2 \rightarrow 3$ processes at NLO, normalized to σ_{dijet} at NLO:

$$\frac{1}{\sigma_{\text{dijet}}} \bigg|_{(\text{N})\text{LO}} \times \frac{d\sigma_{\text{dijet}}}{d\Delta\phi_{\text{dijet}}} \bigg|_{(\text{N})\text{LO}}.$$

Uncertainties due to the renormalization (μ_r) and factorization (μ_f) scales are evaluated by varying the default choice of $\mu_r = \mu_f = p_T^{\text{max}}$ between $p_T^{\text{max}}/2$ and $2p_T^{\text{max}}$ in the following six combinations: $(\mu_r, \mu_f) = (p_T^{\text{max}}/2, p_T^{\text{max}}/2)$, $(2p_T^{\text{max}}, 2p_T^{\text{max}})$, $(p_T^{\text{max}}, p_T^{\text{max}}/2)$, $(p_T^{\text{max}}, 2p_T^{\text{max}})$, $(p_T^{\text{max}}/2, 2p_T^{\text{max}})$, and $(2p_T^{\text{max}}, p_T^{\text{max}})$. These scale variations modify the predictions of the normalized $\Delta\phi_{\text{dijet}}$ distributions by less than 50%. The PDFs and the associated uncertainties were obtained from CTEQ6.6 [19]. The PDF uncertainties were derived using the 22 CTEQ6.6 uncertainty eigenvectors and found to be 9% at $\Delta\phi_{\text{dijet}} \sim \pi/2$ and 2% at $\Delta\phi_{\text{dijet}} < \pi$. Following the proposal of the PDF4LHC working group [23], the impact of other global PDF fits [24–26] was investigated and found to be negligible in the context of this analysis.

Non-perturbative corrections due to hadronization and multiple-parton interactions were applied to the pQCD predictions. The correction factors were determined from the PYTHIA6 and HERWIG++ simulations and modify the predictions from +4% ($\Delta\phi_{\text{dijet}} \sim \pi$) to −13% ($\Delta\phi_{\text{dijet}} \sim \pi/2$). The uncertainty due to the non-perturbative corrections is estimated to be 6% at $\Delta\phi_{\text{dijet}} \sim \pi/2$ and 2% at $\Delta\phi_{\text{dijet}} \sim \pi$. The ratios of the measured $\Delta\phi_{\text{dijet}}$ distributions to the NLO pQCD predictions are shown in Fig. 4. The effect due to the scale variations, as well as the uncertainties due to PDFs and non-perturbative corrections, are also shown. The NLO

predictions provide a good description of the shape of the data distributions over much of the $\Delta\varphi_{\text{dijet}}$ range. Compared to the data, the reduced decorrelation in the theoretical prediction and the increased sensitivity to the μ_r and μ_f scale variations for $\Delta\varphi_{\text{dijet}} < 2\pi/3$ shown in Fig. 4 are attributed to the fact that the pQCD prediction in this region is effectively available only at leading order, since the contribution from tree-level four-parton final states dominates.

The sensitivity of the $\Delta\varphi_{\text{dijet}}$ distributions to initial-state parton shower radiation (ISR) is investigated by varying the input parameter k_{ISR} (PARP(67)) in PYTHIA6 tune D6T. The product of k_{ISR} and the square of the hard-scattering scale gives the maximum allowed parton virtuality (i.e., the maximum allowed p_T) in the initial-state shower. Previous studies have shown that k_{ISR} is the only parameter in PYTHIA6 that has significant impact on the $\Delta\varphi_{\text{dijet}}$ distributions [27]. The default value of k_{ISR} in PYTHIA6 tune D6T is 2.5, determined from the D0 dijet azimuthal decorrelation results [1]. Figure 5 shows comparisons of the measured $\Delta\varphi_{\text{dijet}}$ distributions to PYTHIA6 distributions with various k_{ISR} values. The effects are more pronounced for smaller $\Delta\varphi_{\text{dijet}}$ angles, where multi-gluon radiation dominates. Varying k_{ISR} by ± 0.5 about its default value yields a change of about 30% on the PYTHIA6 prediction for $\Delta\varphi_{\text{dijet}} \sim \pi/2$, suggesting that our results could be used to tune parameters in the MC event generators that control radiative effects in the initial state. In PYTHIA6 tune D6T, the maximum p_T allowed in final-state radiation parton shower is controlled through the parameter PARP(71). We varied the value of this parameter from 2.5 to 8 (the default value is 4.0) and observed less than $\sim 10\%$ changes in the $\Delta\varphi_{\text{dijet}}$ distributions in all p_T regions.

In summary, we have measured dijet azimuthal decorrelations in different leading-jet p_T regions from pp collisions at $\sqrt{s} = 7$ TeV. The PYTHIA6 and HERWIG++ event generators are found to best describe the shape of the measured distributions over the entire range of $\Delta\varphi_{\text{dijet}}$. The predictions from NLO pQCD are in reasonable agreement with the measured distributions, except at small $\Delta\varphi_{\text{dijet}}$ where multiparton radiation effects dominate. The $\Delta\varphi_{\text{dijet}}$ distributions are found to be sensitive to initial-state gluon radiation.

We wish to congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC machine. We thank the technical and administrative staff at CERN and other CMS institutes, and acknowledge support from: FMSR (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, and FAPESP (Brazil); MES (Bulgaria); CERN; CAS, MoST, and NSFC (China); COLCIENCIAS (Colombia); MSES (Croatia); RPF (Cyprus); Academy of Sciences and NICPB (Estonia); Academy of Finland, ME, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); OTKA and NKTH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); NRF and WCU (Korea); LAS (Lithuania); CINVESTAV, CONACYT, SEP, and UASLP-FAI (Mexico); PAEC (Pakistan); SCSR (Poland); FCT (Portugal); JINR (Armenia, Belarus, Georgia, Ukraine, Uzbekistan); MST and MAE (Russia); MSTD (Serbia); MICINN and CPAN (Spain); Swiss Funding Agencies (Switzerland); NSC (Taipei); TUBITAK and TAEK (Turkey); STFC (United Kingdom); DOE and NSF (USA).

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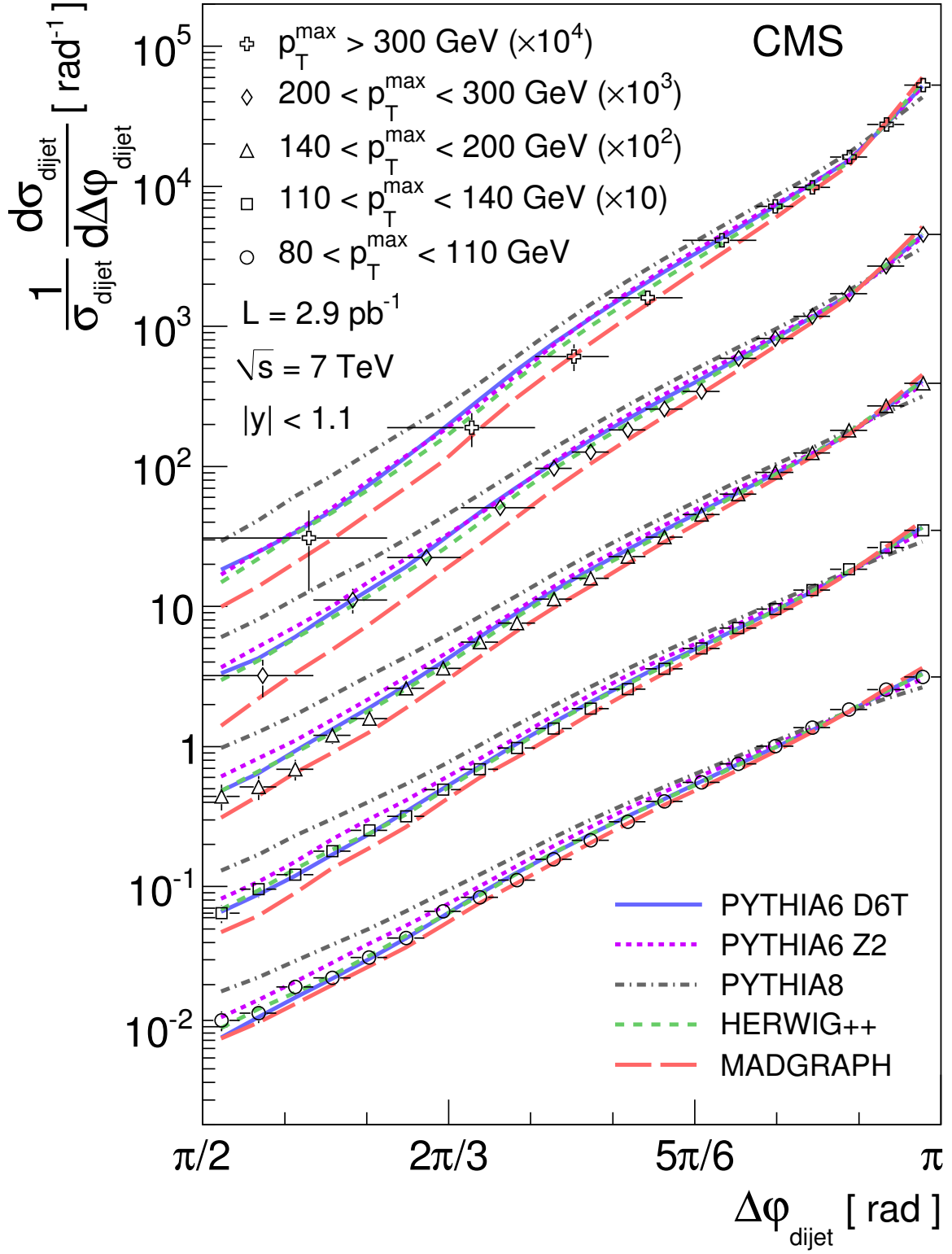


Figure 1: Normalized $\Delta\phi_{\text{dijet}}$ distributions in several p_T^{\max} regions, scaled by the multiplicative factors given in the figure for easier presentation. The curves represent predictions from PYTHIA6, PYTHIA8, HERWIG++, and MADGRAPH. The error bars on the data points include statistical and systematic uncertainties.

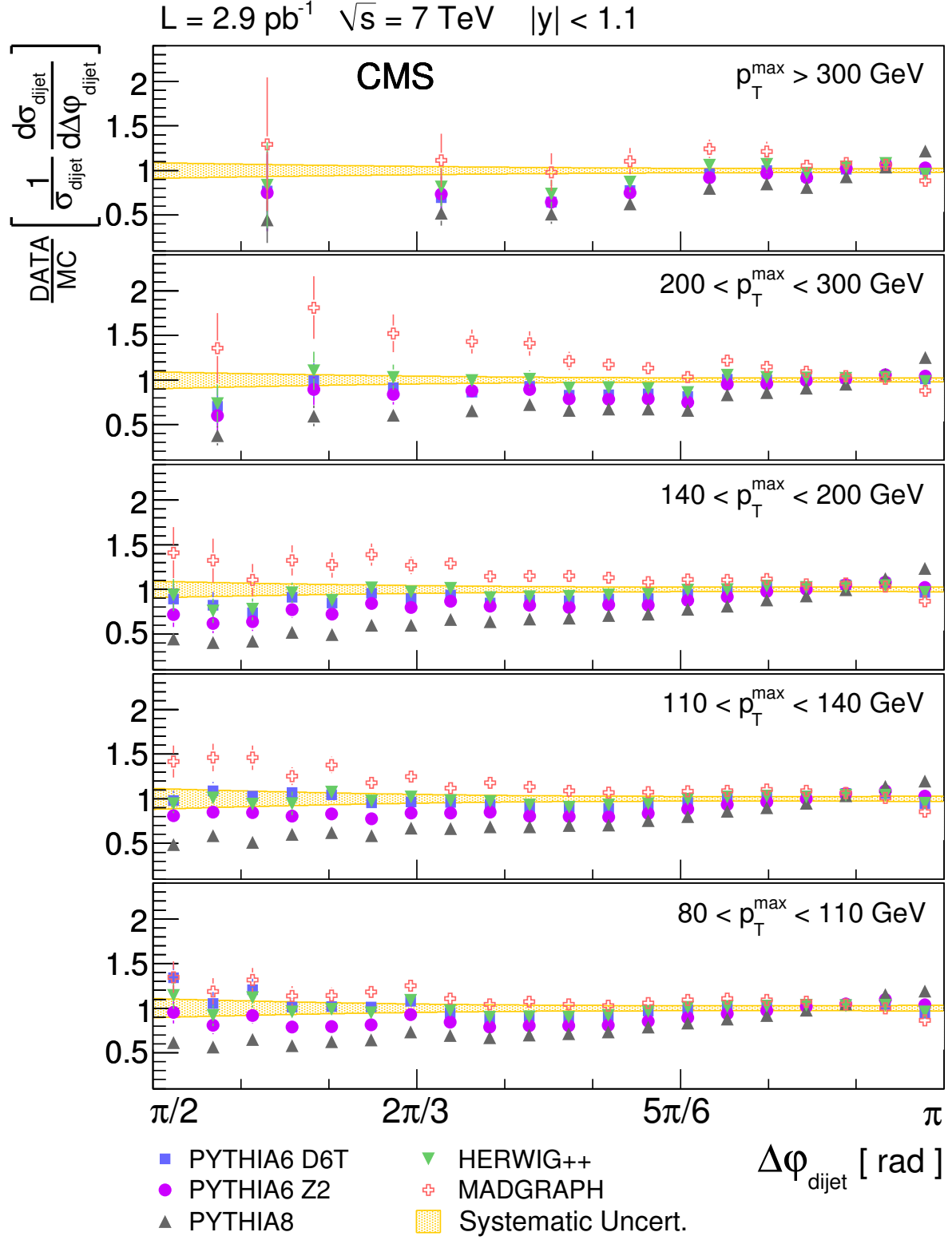


Figure 2: Ratios of measured normalized $\Delta\phi_{\text{dijet}}$ distributions to PYTHIA6, PYTHIA8, HERWIG++, and MADGRAPH predictions in several p_T^{max} regions. The shaded bands indicate the total systematic uncertainty.

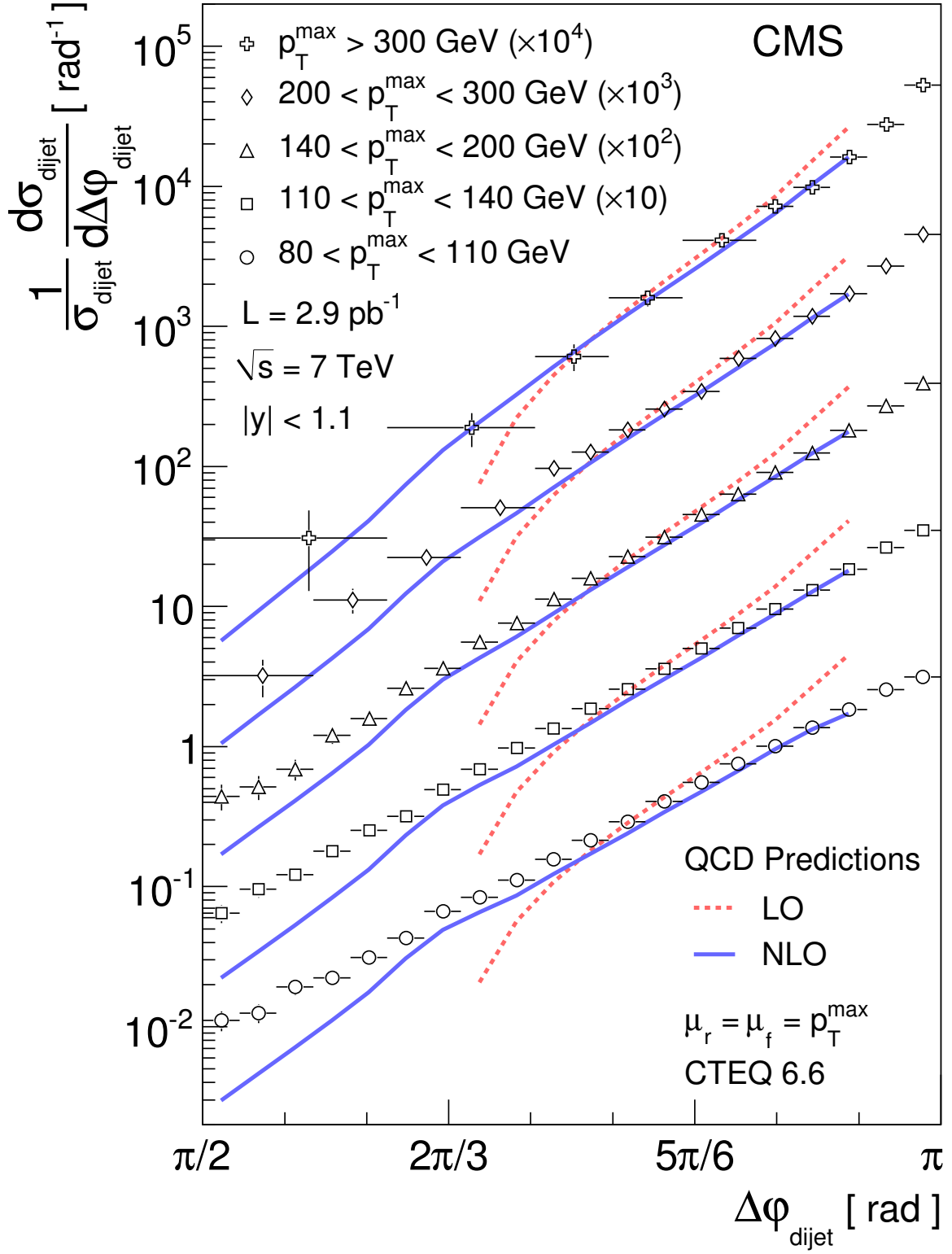


Figure 3: Normalized $\Delta\phi_{\text{dijet}}$ distributions in several p_T^{max} regions, scaled by the multiplicative factors given in the figure for easier presentation. The curves represent predictions from LO (dotted line) and NLO pQCD (solid line). Non-perturbative corrections have been applied to the predictions. The error bars on the data points include statistical and systematic uncertainties.

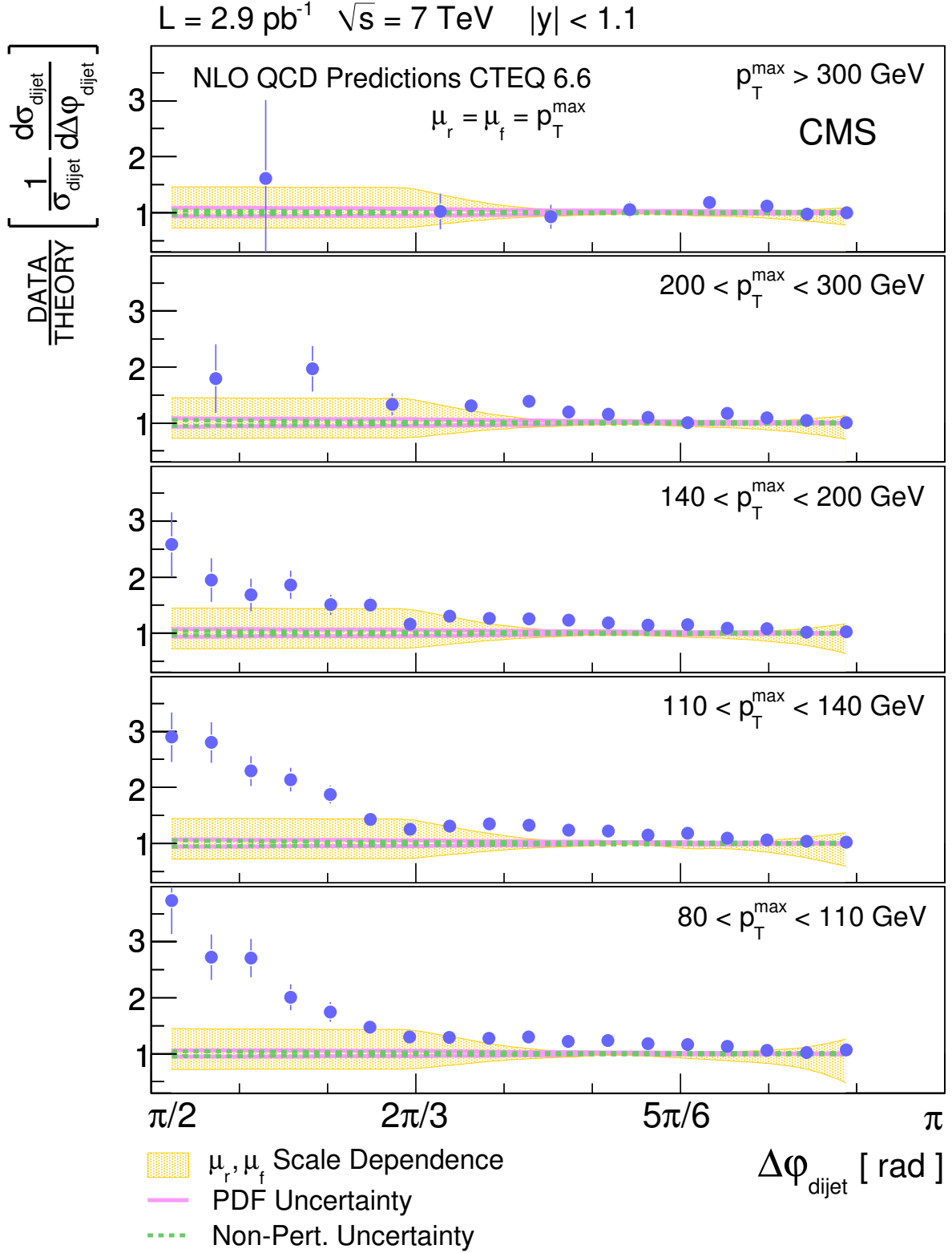


Figure 4: Ratios of measured normalized $\Delta\phi_{\text{dijet}}$ distributions to NLO pQCD predictions with non-perturbative corrections in several p_T^{max} regions. The error bars on the data points include statistical and systematic uncertainties. The effect on the NLO pQCD predictions due to μ_r and μ_f scale variations and PDF uncertainties, as well as the uncertainties from the non-perturbative corrections are shown.

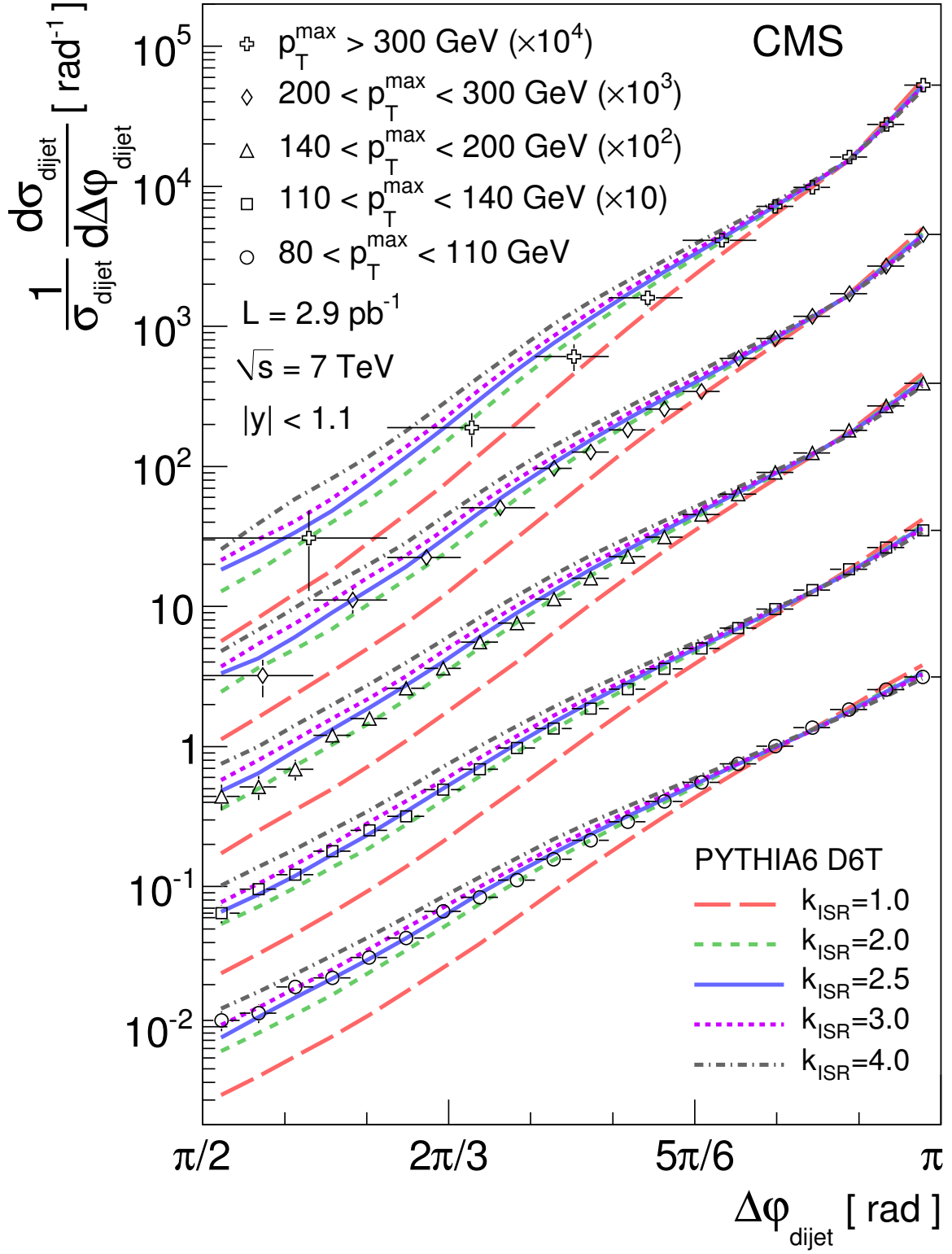


Figure 5: Normalized $\Delta\phi_{\text{dijet}}$ distributions in several p_T^{max} regions, scaled by the multiplicative factors given in the figure for easier presentation. The curves represent the predictions from PYTHIA6 with various values of k_{ISR} . The error bars on the data points include statistical and systematic uncertainties.

A The CMS Collaboration

Yerevan Physics Institute, Yerevan, Armenia

V. Khachatryan, A.M. Sirunyan, A. Tumasyan

Institut für Hochenergiephysik der OeAW, Wien, Austria

W. Adam, T. Bergauer, M. Dragicevic, J. Erö, C. Fabjan, M. Friedl, R. Frühwirth, V.M. Ghete, J. Hammer¹, S. Häseler, C. Hartl, M. Hoch, N. Hörmann, J. Hrubec, M. Jeitler, G. Kasieczka, W. Kiesenhofer, M. Krammer, D. Liko, I. Mikulec, M. Pernicka, H. Rohringer, R. Schöfbeck, J. Strauss, A. Taurok, F. Teischinger, P. Wagner, W. Waltenberger, G. Walzel, E. Widl, C.-E. Wulz

National Centre for Particle and High Energy Physics, Minsk, Belarus

V. Mossolov, N. Shumeiko, J. Suarez Gonzalez

Universiteit Antwerpen, Antwerpen, Belgium

L. Benucci, K. Cerny, E.A. De Wolf, X. Janssen, T. Maes, L. Mucibello, S. Ochesanu, B. Roland, R. Rougny, M. Selvaggi, H. Van Haeve, P. Van Mechelen, N. Van Remortel

Vrije Universiteit Brussel, Brussel, Belgium

S. Beauceron, F. Blekman, S. Blyweert, J. D'Hondt, O. Devroede, R. Gonzalez Suarez, A. Kalogeropoulos, J. Maes, M. Maes, S. Tavernier, W. Van Doninck, P. Van Mulders, G.P. Van Onsem, I. Vilella

Université Libre de Bruxelles, Bruxelles, Belgium

O. Charaf, B. Clerbaux, G. De Lentdecker, V. Dero, A.P.R. Gay, G.H. Hammad, T. Hreus, P.E. Marage, L. Thomas, C. Vander Velde, P. Vanlaer, J. Wickens

Ghent University, Ghent, Belgium

V. Adler, S. Costantini, M. Grunewald, B. Klein, A. Marinov, J. McCartin, D. Ryckbosch, F. Thyssen, M. Tytgat, L. Vanelderen, P. Verwilligen, S. Walsh, N. Zaganidis

Université Catholique de Louvain, Louvain-la-Neuve, Belgium

S. Basegmez, G. Bruno, J. Caudron, L. Ceard, J. De Favereau De Jeneret, C. Delaere, P. Demin, D. Favart, A. Giammanco, G. Grégoire, J. Hollar, V. Lemaitre, J. Liao, O. Militaru, S. Oryn, D. Pagano, A. Pin, K. Piotrkowski, N. Schul

Université de Mons, Mons, Belgium

N. Beliy, T. Caebergs, E. Daubie

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil

G.A. Alves, D. De Jesus Damiao, M.E. Pol, M.H.G. Souza

Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil

W. Carvalho, E.M. Da Costa, C. De Oliveira Martins, S. Fonseca De Souza, L. Mundim, H. Nogima, V. Oguri, W.L. Prado Da Silva, A. Santoro, S.M. Silva Do Amaral, A. Sznajder

Instituto de Fisica Teorica, Universidade Estadual Paulista, Sao Paulo, Brazil

F.A. Dias, M.A.F. Dias, T.R. Fernandez Perez Tomei, E. M. Gregores², F. Marinho, S.F. Novaes, Sandra S. Padula

Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria

N. Darmanov¹, L. Dimitrov, V. Genchev¹, P. Iaydjiev¹, S. Piperov, M. Rodozov, S. Stoykova, G. Sultanov, V. Tcholakov, R. Trayanov, I. Vankov

University of Sofia, Sofia, Bulgaria

M. Dyulendarova, R. Hadjiiska, V. Kozhuharov, L. Litov, E. Marinova, M. Mateev, B. Pavlov, P. Petkov

Institute of High Energy Physics, Beijing, China

J.G. Bian, G.M. Chen, H.S. Chen, C.H. Jiang, D. Liang, S. Liang, J. Wang, J. Wang, X. Wang, Z. Wang, M. Xu, M. Yang, J. Zang, Z. Zhang

State Key Lab. of Nucl. Phys. and Tech., Peking University, Beijing, China

Y. Ban, S. Guo, Y. Guo, W. Li, Y. Mao, S.J. Qian, H. Teng, L. Zhang, B. Zhu, W. Zou

Universidad de Los Andes, Bogota, Colombia

A. Cabrera, B. Gomez Moreno, A.A. Ocampo Rios, A.F. Osorio Oliveros, J.C. Sanabria

Technical University of Split, Split, Croatia

N. Godinovic, D. Lelas, K. Lelas, R. Plestina³, D. Polic, I. Puljak

University of Split, Split, Croatia

Z. Antunovic, M. Dzelalija

Institute Rudjer Boskovic, Zagreb, Croatia

V. Brigljevic, S. Duric, K. Kadija, S. Morovic

University of Cyprus, Nicosia, Cyprus

A. Attikis, M. Galanti, J. Mousa, C. Nicolaou, F. Ptochos, P.A. Razis, H. Rykaczewski

Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt

Y. Assran⁴, M.A. Mahmoud⁵

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

A. Hektor, M. Kadastik, K. Kannike, M. Müntel, M. Raidal, L. Rebane

Department of Physics, University of Helsinki, Helsinki, Finland

V. Azzolini, P. Eerola

Helsinki Institute of Physics, Helsinki, Finland

S. Czellar, J. Härkönen, A. Heikkinen, V. Karimäki, R. Kinnunen, J. Klem, M.J. Kortelainen, T. Lampén, K. Lassila-Perini, S. Lehti, T. Lindén, P. Luukka, T. Mäenpää, E. Tuominen, J. Tuominiemi, E. Tuovinen, D. Ungaro, L. Wendland

Lappeenranta University of Technology, Lappeenranta, Finland

K. Banzuzi, A. Korpela, T. Tuuva

Laboratoire d'Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France

D. Sillou

DSM/IRFU, CEA/Saclay, Gif-sur-Yvette, France

M. Besancon, S. Choudhury, M. Dejardin, D. Denegri, B. Fabbro, J.L. Faure, F. Ferri, S. Ganjour, F.X. Gentit, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, E. Locci, J. Malcles, M. Marionneau, L. Millischer, J. Rander, A. Rosowsky, I. Shreyber, M. Titov, P. Verrecchia

Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France

S. Baffioni, F. Beaudette, L. Bianchini, M. Bluj⁶, C. Broutin, P. Busson, C. Charlot, T. Dahms, L. Dobrzynski, R. Granier de Cassagnac, M. Haguenauer, P. Miné, C. Mironov, C. Ochando, P. Paganini, D. Sabes, R. Salerno, Y. Sirois, C. Thiebaux, B. Wyslouch⁷, A. Zabi

Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France

J.-L. Agram⁸, J. Andrea, A. Besson, D. Bloch, D. Bodin, J.-M. Brom, M. Cardaci, E.C. Chabert, C. Collard, E. Conte⁸, F. Drouhin⁸, C. Ferro, J.-C. Fontaine⁸, D. Gelé, U. Goerlach, S. Greder, P. Juillot, M. Karim⁸, A.-C. Le Bihan, Y. Mikami, P. Van Hove

Centre de Calcul de l'Institut National de Physique Nucleaire et de Physique des Particules (IN2P3), Villeurbanne, France

F. Fassi, D. Mercier

Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France

C. Baty, N. Beaupere, M. Bedjidian, O. Bondu, G. Boudoul, D. Boumediene, H. Brun, N. Chanon, R. Chierici, D. Contardo, P. Depasse, H. El Mamouni, A. Falkiewicz, J. Fay, S. Gascon, B. Ille, T. Kurca, T. Le Grand, M. Lethuillier, L. Mirabito, S. Perries, V. Sordini, S. Tosi, Y. Tschudi, P. Verdier, H. Xiao

E. Andronikashvili Institute of Physics, Academy of Science, Tbilisi, Georgia

L. Megrelishvili, V. Roinishvili

Institute of High Energy Physics and Informatization, Tbilisi State University, Tbilisi, Georgia

D. Lomidze

RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany

G. Anagnostou, M. Edelhoff, L. Feld, N. Heracleous, O. Hindrichs, R. Jussen, K. Klein, J. Merz, N. Mohr, A. Ostapchuk, A. Perieanu, F. Raupach, J. Sammet, S. Schael, D. Sprenger, H. Weber, M. Weber, B. Wittmer

RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany

M. Ata, W. Bender, M. Erdmann, J. Frangenheim, T. Hebbeker, A. Hinzmann, K. Hoepfner, C. Hof, T. Klimovich, D. Klingebiel, P. Kreuzer, D. Lanske[†], C. Magass, G. Masetti, M. Merschmeyer, A. Meyer, P. Papacz, H. Pieta, H. Reithler, S.A. Schmitz, L. Sonnenschein, J. Steggemann, D. Teyssier

RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany

M. Bontenackels, M. Davids, M. Duda, G. Flügge, H. Geenen, M. Giffels, W. Haj Ahmad, D. Heydhausen, T. Kress, Y. Kuessel, A. Linn, A. Nowack, L. Perchalla, O. Pooth, J. Rennefeld, P. Sauerland, A. Stahl, M. Thomas, D. Tornier, M.H. Zoeller

Deutsches Elektronen-Synchrotron, Hamburg, Germany

M. Aldaya Martin, W. Behrenhoff, U. Behrens, M. Bergholz⁹, K. Borras, A. Cakir, A. Campbell, E. Castro, D. Dammann, G. Eckerlin, D. Eckstein, A. Flossdorf, G. Flucke, A. Geiser, I. Glushkov, J. Hauk, H. Jung, M. Kasemann, I. Katkov, P. Katsas, C. Kleinwort, H. Kluge, A. Knutsson, D. Krücker, E. Kuznetsova, W. Lange, W. Lohmann⁹, R. Mankel, M. Marienfeld, I.-A. Melzer-Pellmann, A.B. Meyer, J. Mnich, A. Mussgiller, J. Olzem, A. Parenti, A. Raspereza, A. Raval, R. Schmidt⁹, T. Schoerner-Sadenius, N. Sen, M. Stein, J. Tomaszewska, D. Volyanskyy, R. Walsh, C. Wissing

University of Hamburg, Hamburg, Germany

C. Autermann, S. Bobrovskiy, J. Draeger, H. Enderle, U. Gebbert, K. Kaschube, G. Kaussen, R. Klanner, J. Lange, B. Mura, S. Naumann-Emme, F. Nowak, N. Pietsch, C. Sander, H. Schettler, P. Schleper, M. Schröder, T. Schum, J. Schwandt, A.K. Srivastava, H. Stadie, G. Steinbrück, J. Thomsen, R. Wolf

Institut für Experimentelle Kernphysik, Karlsruhe, Germany

C. Barth, J. Bauer, V. Buege, T. Chwalek, W. De Boer, A. Dierlamm, G. Dirkes, M. Feindt, J. Gruschke, C. Hackstein, F. Hartmann, S.M. Heindl, M. Heinrich, H. Held, K.H. Hoffmann, S. Honc, T. Kuhr, D. Martschei, S. Mueller, Th. Müller, M. Niegel, O. Oberst, A. Oehler, J. Ott, T. Peiffer, D. Piparo, G. Quast, K. Rabbertz, F. Ratnikov, M. Renz, C. Saout, A. Scheurer, P. Schieferdecker, F.-P. Schilling, G. Schott, H.J. Simonis, F.M. Stober, D. Troendle, J. Wagner-Kuhr, M. Zeise, V. Zhukov¹⁰, E.B. Ziebarth

Institute of Nuclear Physics "Demokritos", Aghia Paraskevi, Greece

G. Daskalakis, T. Gerasis, S. Kesisoglou, A. Kyriakis, D. Loukas, I. Manolakos, A. Markou, C. Markou, C. Mavrommatis, E. Ntomari, E. Petrakou

University of Athens, Athens, Greece

L. Gouskos, T.J. Mertzimekis, A. Panagiotou

University of Ioánnina, Ioánnina, Greece

I. Evangelou, C. Foudas, P. Kokkas, N. Manthos, I. Papadopoulos, V. Patras, F.A. Triantis

KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary

A. Aranyi, G. Bencze, L. Boldizsar, G. Debreczeni, C. Hajdu¹, D. Horvath¹¹, A. Kapusi, K. Krajczar¹², A. Laszlo, F. Sikler, G. Vesztergombi¹²

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

N. Beni, J. Molnar, J. Palinkas, Z. Szillasi, V. Veszpremi

University of Debrecen, Debrecen, Hungary

P. Raics, Z.L. Trocsanyi, B. Ujvari

Panjab University, Chandigarh, India

S. Bansal, S.B. Beri, V. Bhatnagar, N. Dhingra, R. Gupta, M. Jindal, M. Kaur, J.M. Kohli, M.Z. Mehta, N. Nishu, L.K. Saini, A. Sharma, A.P. Singh, J.B. Singh, S.P. Singh

University of Delhi, Delhi, India

S. Ahuja, S. Bhattacharya, B.C. Choudhary, P. Gupta, S. Jain, S. Jain, A. Kumar, R.K. Shivpuri

Bhabha Atomic Research Centre, Mumbai, India

R.K. Choudhury, D. Dutta, S. Kailas, S.K. Kataria, A.K. Mohanty¹, L.M. Pant, P. Shukla

Tata Institute of Fundamental Research - EHEP, Mumbai, India

T. Aziz, M. Guchait¹³, A. Gurtu, M. Maity¹⁴, D. Majumder, G. Majumder, K. Mazumdar, G.B. Mohanty, A. Saha, K. Sudhakar, N. Wickramage

Tata Institute of Fundamental Research - HECR, Mumbai, India

S. Banerjee, S. Dugad, N.K. Mondal

Institute for Research and Fundamental Sciences (IPM), Tehran, Iran

H. Arfaei, H. Bakhshiansohi, S.M. Etesami, A. Fahim, M. Hashemi, A. Jafari, M. Khakzad, A. Mohammadi, M. Mohammadi Najafabadi, S. Paktinat Mehdiabadi, B. Safarzadeh, M. Zeinali

INFN Sezione di Bari ^a, Università di Bari ^b, Politecnico di Bari ^c, Bari, Italy

M. Abbrescia^{a,b}, L. Barbone^{a,b}, C. Calabria^{a,b}, A. Colaleo^a, D. Creanza^{a,c}, N. De Filippis^{a,c}, M. De Palma^{a,b}, A. Dimitrov^a, L. Fiore^a, G. Iaselli^{a,c}, L. Lusito^{a,b,1}, G. Maggi^{a,c}, M. Maggi^a, N. Manna^{a,b}, B. Marangelli^{a,b}, S. My^{a,c}, S. Nuzzo^{a,b}, N. Pacifico^{a,b}, G.A. Pierro^a, A. Pompili^{a,b}, G. Pugliese^{a,c}, F. Romano^{a,c}, G. Roselli^{a,b}, G. Selvaggi^{a,b}, L. Silvestris^a, R. Trentadue^a, S. Tupputi^{a,b}, G. Zito^a

INFN Sezione di Bologna ^a, Università di Bologna ^b, Bologna, Italy

G. Abbiendi^a, A.C. Benvenuti^a, D. Bonacorsi^a, S. Braibant-Giacomelli^{a,b}, L. Brigliadori^a, P. Capiluppi^{a,b}, A. Castro^{a,b}, F.R. Cavallo^a, M. Cuffiani^{a,b}, G.M. Dallavalle^a, F. Fabbri^a, A. Fanfani^{a,b}, D. Fasanella^a, P. Giacomelli^a, M. Giunta^a, S. Marcellini^a, M. Meneghelli^{a,b}, A. Montanari^a, F.L. Navarria^{a,b}, F. Odorici^a, A. Perrotta^a, F. Primavera^a, A.M. Rossi^{a,b}, T. Rovelli^{a,b}, G. Siroli^{a,b}, R. Travaglini^{a,b}

INFN Sezione di Catania ^a, Università di Catania ^b, Catania, Italy

S. Albergo^{a,b}, G. Cappello^{a,b}, M. Chiorboli^{a,b,1}, S. Costa^{a,b}, A. Tricomi^{a,b}, C. Tuve^a

INFN Sezione di Firenze ^a, Università di Firenze ^b, Firenze, Italy

G. Barbagli^a, V. Ciulli^{a,b}, C. Civinini^a, R. D'Alessandro^{a,b}, E. Focardi^{a,b}, S. Frosali^{a,b}, E. Gallo^a, C. Genta^a, S. Gonzi^{a,b}, P. Lenzi^{a,b}, M. Meschini^a, S. Paoletti^a, G. Sguazzoni^a, A. Tropiano^{a,1}

INFN Laboratori Nazionali di Frascati, Frascati, Italy

L. Benussi, S. Bianco, S. Colafranceschi¹⁵, F. Fabbri, D. Piccolo

INFN Sezione di Genova, Genova, Italy

P. Fabbriatore, R. Musenich

INFN Sezione di Milano-Bicocca ^a, Università di Milano-Bicocca ^b, Milano, Italy

A. Benaglia^{a,b}, F. De Guio^{a,b,1}, L. Di Matteo^{a,b}, A. Ghezzi^{a,b,1}, M. Malberti^{a,b}, S. Malvezzi^a, A. Martelli^{a,b}, A. Massironi^{a,b}, D. Menasce^a, L. Moroni^a, M. Paganoni^{a,b}, D. Pedrini^a, S. Ragazzi^{a,b}, N. Redaelli^a, S. Sala^a, T. Tabarelli de Fatis^{a,b}, V. Tancini^{a,b}

INFN Sezione di Napoli ^a, Università di Napoli "Federico II" ^b, Napoli, Italy

S. Buontempo^a, C.A. Carrillo Montoya^a, A. Cimmino^{a,b}, A. De Cosa^{a,b}, M. De Gruttola^{a,b}, F. Fabozzi^{a,16}, A.O.M. Iorio^a, L. Lista^a, M. Merola^{a,b}, P. Noli^{a,b}, P. Paolucci^a

INFN Sezione di Padova ^a, Università di Padova ^b, Università di Trento (Trento) ^c, Padova, Italy

P. Azzi^a, N. Bacchetta^a, P. Bellan^{a,b}, D. Bisello^{a,b}, A. Branca^a, R. Carlin^{a,b}, P. Checchia^a, M. De Mattia^{a,b}, T. Dorigo^a, F. Gasparini^{a,b}, U. Gasparini^{a,b}, P. Giubilato^{a,b}, F. Gonella^a, A. Gresele^{a,c}, S. Lacaprara^{a,17}, I. Lazzizzera^{a,c}, M. Margoni^{a,b}, M. Mazzucato^a, A.T. Meneguzzo^{a,b}, M. Nespolo^{a,1}, L. Perrozzi^{a,1}, N. Pozzobon^{a,b}, P. Ronchese^{a,b}, F. Simonetto^{a,b}, E. Torassa^a, M. Tosi^{a,b}, A. Triossi^a, S. Vanini^{a,b}, P. Zotto^{a,b}, G. Zumerle^{a,b}

INFN Sezione di Pavia ^a, Università di Pavia ^b, Pavia, Italy

P. Baesso^{a,b}, U. Berzano^a, C. Riccardi^{a,b}, P. Torre^{a,b}, P. Vitulo^{a,b}, C. Viviani^{a,b}

INFN Sezione di Perugia ^a, Università di Perugia ^b, Perugia, Italy

M. Biasini^{a,b}, G.M. Bilei^a, B. Caponeri^{a,b}, L. Fano^{a,b}, P. Lariccia^{a,b}, A. Lucaroni^{a,b,1}, G. Mantovani^{a,b}, M. Menichelli^a, A. Nappi^{a,b}, A. Santocchia^{a,b}, L. Servoli^a, S. Taroni^{a,b}, M. Valdata^{a,b}, R. Volpe^{a,b,1}

INFN Sezione di Pisa ^a, Università di Pisa ^b, Scuola Normale Superiore di Pisa ^c, Pisa, Italy

P. Azzurri^{a,c}, G. Bagliesi^a, J. Bernardini^{a,b}, T. Boccali^{a,1}, G. Broccolo^{a,c}, R. Castaldi^a, R.T. D'Agnolo^{a,c}, R. Dell'Orso^a, F. Fiori^{a,b}, L. Foà^{a,c}, A. Giassi^a, A. Kraan^a, F. Ligabue^{a,c}, T. Lomtadze^a, L. Martini^{a,18}, A. Messineo^{a,b}, F. Palla^a, F. Palmonari^a, S. Sarkar^{a,c}, G. Segneri^a, A.T. Serban^a, P. Spagnolo^a, R. Tenchini^a, G. Tonelli^{a,b,1}, A. Venturi^{a,1}, P.G. Verdini^a

INFN Sezione di Roma ^a, Università di Roma "La Sapienza" ^b, Roma, Italy

L. Barone^{a,b}, F. Cavallari^a, D. Del Re^{a,b}, E. Di Marco^{a,b}, M. Diemoz^a, D. Franci^{a,b}, M. Grassi^a, E. Longo^{a,b}, G. Organtini^{a,b}, A. Palma^{a,b}, F. Pandolfi^{a,b,1}, R. Paramatti^a, S. Rahatlou^{a,b}

INFN Sezione di Torino ^a, Università di Torino ^b, Università del Piemonte Orientale (Novara) ^c, Torino, Italy

N. Amapane^{a,b}, R. Arcidiacono^{a,c}, S. Argiro^{a,b}, M. Arneodo^{a,c}, C. Biino^a, C. Botta^{a,b,1}, N. Cartiglia^a, R. Castello^{a,b}, M. Costa^{a,b}, N. Demaria^a, A. Graziano^{a,b,1}, C. Mariotti^a, M. Marone^{a,b}, S. Maselli^a, E. Migliore^{a,b}, G. Mila^{a,b}, V. Monaco^{a,b}, M. Musich^{a,b}, M.M. Obertino^{a,c}, N. Pastrone^a, M. Pelliccioni^{a,b,1}, A. Romero^{a,b}, M. Ruspa^{a,c}, R. Sacchi^{a,b}, V. Sola^{a,b}, A. Solano^{a,b}, A. Staiano^a, D. Trocino^{a,b}, A. Vilela Pereira^{a,b,1}

INFN Sezione di Trieste ^a, Università di Trieste ^b, Trieste, Italy

S. Belforte^a, F. Cossutti^a, G. Della Ricca^{a,b}, B. Gobbo^a, D. Montanino^{a,b}, A. Penzo^a

Kangwon National University, Chunchon, Korea

S.G. Heo

Kyungpook National University, Daegu, Korea

S. Chang, J. Chung, D.H. Kim, G.N. Kim, J.E. Kim, D.J. Kong, H. Park, D. Son, D.C. Son

Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea

Zero Kim, J.Y. Kim, S. Song

Korea University, Seoul, Korea

S. Choi, B. Hong, M. Jo, H. Kim, J.H. Kim, T.J. Kim, K.S. Lee, D.H. Moon, S.K. Park, H.B. Rhee, E. Seo, S. Shin, K.S. Sim

University of Seoul, Seoul, Korea

M. Choi, S. Kang, H. Kim, C. Park, I.C. Park, S. Park, G. Ryu

Sungkyunkwan University, Suwon, Korea

Y. Choi, Y.K. Choi, J. Goh, J. Lee, S. Lee, H. Seo, I. Yu

Vilnius University, Vilnius, Lithuania

M.J. Bilinskas, I. Grigelionis, M. Janulis, D. Martisiute, P. Petrov, T. Sabonis

Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico

H. Castilla Valdez, E. De La Cruz Burelo, R. Lopez-Fernandez, A. Sánchez Hernández, L.M. Villasenor-Cendejas

Universidad Iberoamericana, Mexico City, Mexico

S. Carrillo Moreno, F. Vazquez Valencia

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

H.A. Salazar Ibarguen

Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico

E. Casimiro Linares, A. Morelos Pineda, M.A. Reyes-Santos

University of Auckland, Auckland, New Zealand

P. Allfrey, D. Krofcheck

University of Canterbury, Christchurch, New Zealand

P.H. Butler, R. Doesburg, H. Silverwood

National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan

M. Ahmad, I. Ahmed, M.I. Asghar, H.R. Hoorani, W.A. Khan, T. Khurshid, S. Qazi

Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland
M. Cwiok, W. Dominik, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski

Soltan Institute for Nuclear Studies, Warsaw, Poland

T. Frueboes, R. Gokieli, M. Górski, M. Kazana, K. Nawrocki, K. Romanowska-Rybinska, M. Szleper, G. Wrochna, P. Zalewski

Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal

N. Almeida, A. David, P. Faccioli, P.G. Ferreira Parracho, M. Gallinaro, P. Martins, P. Musella, A. Nayak, P.Q. Ribeiro, J. Seixas, P. Silva, J. Varela, H.K. Wöhri

Joint Institute for Nuclear Research, Dubna, Russia

I. Belotelov, P. Bunin, M. Finger, M. Finger Jr., I. Golutvin, A. Kamenev, V. Karjavin, G. Kozlov, A. Lanev, P. Moisenz, V. Palichik, V. Perelygin, S. Shmatov, V. Smirnov, A. Volodko, A. Zarubin

Petersburg Nuclear Physics Institute, Gatchina (St Petersburg), Russia

N. Bondar, V. Golovtsov, Y. Ivanov, V. Kim, P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, V. Sulimov, L. Uvarov, S. Vasilov, A. Vorobyev

Institute for Nuclear Research, Moscow, Russia

Yu. Andreev, S. Gninenko, N. Golubev, M. Kirsanov, N. Krasnikov, V. Matveev, A. Pashenkov, A. Toropin, S. Troitsky

Institute for Theoretical and Experimental Physics, Moscow, Russia

V. Epshteyn, V. Gavrilov, V. Kaftanov[†], M. Kossov¹, A. Krokhotin, N. Lychkovskaya, G. Safronov, S. Semenov, V. Stolin, E. Vlasov, A. Zhokin

Moscow State University, Moscow, Russia

E. Boos, M. Dubinin¹⁹, L. Dudko, A. Ershov, A. Gribushin, O. Kodolova, I. Lokhtin, S. Obraztsov, S. Petrushanko, L. Sarycheva, V. Savrin, A. Snigirev

P.N. Lebedev Physical Institute, Moscow, Russia

V. Andreev, M. Azarkin, I. Dremin, M. Kirakosyan, S.V. Rusakov, A. Vinogradov

State Research Center of Russian Federation, Institute for High Energy Physics, Protvino, Russia

I. Azhgirey, S. Bitioukov, V. Grishin¹, V. Kachanov, D. Konstantinov, A. Korablev, V. Krychkin, V. Petrov, R. Ryutin, S. Slabospitsky, A. Sobol, L. Tourtchanovitch, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov

University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia

P. Adzic²⁰, M. Djordjevic, D. Krpic²⁰, J. Milosevic

Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain

M. Aguilar-Benitez, J. Alcaraz Maestre, P. Arce, C. Battilana, E. Calvo, M. Cepeda, M. Cerrada, N. Colino, B. De La Cruz, C. Diez Pardos, D. Domínguez Vázquez, C. Fernandez Bedoya, J.P. Fernández Ramos, A. Ferrando, J. Flix, M.C. Fouz, P. Garcia-Abia, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, G. Merino, J. Puerta Pelayo, I. Redondo, L. Romero, J. Santaolalla, C. Willmott

Universidad Autónoma de Madrid, Madrid, Spain

C. Albajar, G. Codispoti, J.F. de Trocóniz

Universidad de Oviedo, Oviedo, Spain

J. Cuevas, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, L. Lloret Iglesias, J.M. Vizan Garcia

Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain

J.A. Brochero Cifuentes, I.J. Cabrillo, A. Calderon, M. Chamizo Llatas, S.H. Chuang, J. Duarte Campderros, M. Felcini²¹, M. Fernandez, G. Gomez, J. Gonzalez Sanchez, C. Jorda, P. Lobelle Pardo, A. Lopez Virto, J. Marco, R. Marco, C. Martinez Rivero, F. Matorras, F.J. Munoz Sanchez, J. Piedra Gomez²², T. Rodrigo, A. Ruiz Jimeno, L. Scodellaro, M. Sobron Sanudo, I. Vila, R. Vilar Cortabitarte

CERN, European Organization for Nuclear Research, Geneva, Switzerland

D. Abbaneo, E. Auffray, G. Auzinger, P. Baillon, A.H. Ball, D. Barney, A.J. Bell²³, D. Benedetti, C. Bernet³, W. Bialas, P. Bloch, A. Bocci, S. Bolognesi, H. Breuker, G. Brona, K. Bunkowski, T. Camporesi, E. Cano, G. Cerminara, T. Christiansen, J.A. Coarasa Perez, B. Curé, D. D'Enterria, A. De Roeck, S. Di Guida, F. Duarte Ramos, A. Elliott-Peisert, B. Frisch, W. Funk, A. Gaddi, S. Gennai, G. Georgiou, H. Gerwig, D. Gigi, K. Gill, D. Giordano, F. Glege, R. Gomez-Reino Garrido, M. Gouzevitch, P. Govoni, S. Gowdy, L. Guiducci, M. Hansen, J. Harvey, J. Hegeman, B. Hegner, C. Henderson, G. Hesketh, H.F. Hoffmann, A. Honma, V. Innocente, P. Janot, K. Kaadze, E. Karavakis, P. Lecoq, C. Lourenço, A. Macpherson, T. Mäki, L. Malgeri, M. Mannelli, L. Masetti, F. Meijers, S. Mersi, E. Meschi, R. Moser, M.U. Mozer, M. Mulders, E. Nesvold¹, M. Nguyen, T. Orimoto, L. Orsini, E. Perez, A. Petrilli, A. Pfeiffer, M. Pierini, M. Pimiä, G. Polese, A. Racz, J. Rodrigues Antunes, G. Rolandi²⁴, T. Rommelskirchen, C. Rovelli²⁵, M. Rovere, H. Sakulin, C. Schäfer, C. Schwick, I. Segoni, A. Sharma, P. Siegrist, M. Simon, P. Sphicas²⁶, D. Spiga, M. Spiropulu¹⁹, F. Stöckli, M. Stoye, P. Tropea, A. Tsiros, A. Tsyganov, G.I. Veres¹², P. Vichoudis, M. Voutilainen, W.D. Zeuner

Paul Scherrer Institut, Villigen, Switzerland

W. Bertl, K. Deiters, W. Erdmann, K. Gabathuler, R. Horisberger, Q. Ingram, H.C. Kaestli, S. König, D. Kotlinski, U. Langenegger, F. Meier, D. Renker, T. Rohe, J. Sibille²⁷, A. Starodumov²⁸

Institute for Particle Physics, ETH Zurich, Zurich, Switzerland

P. Bortignon, L. Caminada²⁹, Z. Chen, S. Cittolin, G. Dissertori, M. Dittmar, J. Eugster, K. Freudenreich, C. Grab, A. Hervé, W. Hintz, P. Lecomte, W. Lustermann, C. Marchica²⁹, P. Martinez Ruiz del Arbol, P. Meridiani, P. Milenovic³⁰, F. Moortgat, P. Nef, F. Nessi-Tedaldi, L. Pape, F. Pauss, T. Punz, A. Rizzi, F.J. Ronga, M. Rossini, L. Sala, A.K. Sanchez, M.-C. Sawley, B. Stieger, L. Tauscher[†], A. Thea, K. Theofilatos, D. Treille, C. Urscheler, R. Wallny, M. Weber, L. Wehrli, J. Weng

Universität Zürich, Zurich, Switzerland

E. Aguiló, C. Amsler, V. Chiochia, S. De Visscher, C. Favaro, M. Ivova Rikova, B. Millan Mejias, C. Regenfus, P. Robmann, A. Schmidt, H. Snoek

National Central University, Chung-Li, Taiwan

Y.H. Chang, K.H. Chen, W.T. Chen, S. Dutta, A. Go, C.M. Kuo, S.W. Li, W. Lin, M.H. Liu, Z.K. Liu, Y.J. Lu, D. Mekterovic, J.H. Wu, S.S. Yu

National Taiwan University (NTU), Taipei, Taiwan

P. Bartalini, P. Chang, Y.H. Chang, Y.W. Chang, Y. Chao, K.F. Chen, W.-S. Hou, Y. Hsiung, K.Y. Kao, Y.J. Lei, R.-S. Lu, J.G. Shiu, Y.M. Tzeng, M. Wang

Cukurova University, Adana, Turkey

A. Adiguzel, M.N. Bakirci³¹, S. Cerci³², C. Dozen, I. Dumanoglu, E. Eskut, S. Girgis, G. Gokbulut, Y. Guler, E. Gurpinar, I. Hos, E.E. Kangal, T. Karaman, A. Kayis Topaksu, A. Nart, G. Onengut, K. Ozdemir, S. Ozturk, A. Polatoz, K. Sogut³³, B. Tali, H. Topakli³¹, D. Uzun, L.N. Vergili, M. Vergili, C. Zorbilmez

Middle East Technical University, Physics Department, Ankara, Turkey

I.V. Akin, T. Aliev, S. Bilmis, M. Deniz, H. Gamsizkan, A.M. Guler, K. Ocalan, A. Ozpineci, M. Serin, R. Sever, U.E. Surat, E. Yildirim, M. Zeyrek

Bogazici University, Istanbul, Turkey

M. Deliomeroglu, D. Demir³⁴, E. Gülmez, A. Halu, B. Isildak, M. Kaya³⁵, O. Kaya³⁵, S. Ozkorucuklu³⁶, N. Sonmez³⁷

National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine

L. Levchuk

University of Bristol, Bristol, United Kingdom

P. Bell, F. Bostock, J.J. Brooke, T.L. Cheng, E. Clement, D. Cussans, R. Frazier, J. Goldstein, M. Grimes, M. Hansen, D. Hartley, G.P. Heath, H.F. Heath, B. Huckvale, J. Jackson, L. Kreczko, S. Metson, D.M. Newbold³⁸, K. Nirunpong, A. Poll, S. Senkin, V.J. Smith, S. Ward

Rutherford Appleton Laboratory, Didcot, United Kingdom

L. Basso, K.W. Bell, A. Belyaev, C. Brew, R.M. Brown, B. Camanzi, D.J.A. Cockerill, J.A. Coughlan, K. Harder, S. Harper, B.W. Kennedy, E. Olaiya, D. Petyt, B.C. Radburn-Smith, C.H. Shepherd-Themistocleous, I.R. Tomalin, W.J. Womersley, S.D. Worm

Imperial College, London, United Kingdom

R. Bainbridge, G. Ball, J. Ballin, R. Beuselinck, O. Buchmuller, D. Colling, N. Cripps, M. Cutajar, G. Davies, M. Della Negra, J. Fulcher, D. Futyan, A. Guneratne Bryer, G. Hall, Z. Hatherell, J. Hays, G. Iles, G. Karapostoli, L. Lyons, A.-M. Magnan, J. Marrouche, R. Nandi, J. Nash, A. Nikitenko²⁸, A. Papageorgiou, M. Pesaresi, K. Petridis, M. Pioppi³⁹, D.M. Raymond, N. Rompotis, A. Rose, M.J. Ryan, C. Seez, P. Sharp, A. Sparrow, A. Tapper, S. Tourneur, M. Vazquez Acosta, T. Virdee, S. Wakefield, D. Wardrope, T. Whyntie

Brunel University, Uxbridge, United Kingdom

M. Barrett, M. Chadwick, J.E. Cole, P.R. Hobson, A. Khan, P. Kyberd, D. Leslie, W. Martin, I.D. Reid, L. Teodorescu

Baylor University, Waco, USA

K. Hatakeyama

Boston University, Boston, USA

T. Bose, E. Carrera Jarrin, A. Clough, C. Fantasia, A. Heister, J. St. John, P. Lawson, D. Lazic, J. Rohlf, D. Sperka, L. Sulak

Brown University, Providence, USA

A. Avetisyan, S. Bhattacharya, J.P. Chou, D. Cutts, A. Ferapontov, U. Heintz, S. Jabeen, G. Kukartsev, G. Landsberg, M. Narain, D. Nguyen, M. Segala, T. Speer, K.V. Tsang

University of California, Davis, Davis, USA

M.A. Borgia, R. Breedon, M. Calderon De La Barca Sanchez, D. Cebra, S. Chauhan, M. Chertok, J. Conway, P.T. Cox, J. Dolen, R. Erbacher, E. Friis, W. Ko, A. Kopecky, R. Lander, H. Liu, S. Maruyama, T. Miceli, M. Nikolic, D. Pellett, J. Robles, S. Salur, T. Schwarz, M. Searle, J. Smith, M. Squires, M. Tripathi, R. Vasquez Sierra, C. Veelken

University of California, Los Angeles, Los Angeles, USA

V. Andreev, K. Arisaka, D. Cline, R. Cousins, A. Deisher, J. Duris, S. Erhan, C. Farrell, J. Hauser, M. Ignatenko, C. Jarvis, C. Plager, G. Rakness, P. Schlein[†], J. Tucker, V. Valuev

University of California, Riverside, Riverside, USA

J. Babb, R. Clare, J. Ellison, J.W. Gary, F. Giordano, G. Hanson, G.Y. Jeng, S.C. Kao, F. Liu, H. Liu, A. Luthra, H. Nguyen, G. Pasztor⁴⁰, A. Satpathy, B.C. Shen[†], R. Stringer, J. Sturdy, S. Sumowidagdo, R. Wilken, S. Wimpenny

University of California, San Diego, La Jolla, USA

W. Andrews, J.G. Branson, G.B. Cerati, E. Dusingberre, D. Evans, F. Golf, A. Holzner, R. Kelley, M. Lebourgeois, J. Letts, B. Mangano, J. Muelmenstaedt, S. Padhi, C. Palmer, G. Petrucciani, H. Pi, M. Pieri, R. Ranieri, M. Sani, V. Sharma¹, S. Simon, Y. Tu, A. Vartak, F. Würthwein, A. Yagil

University of California, Santa Barbara, Santa Barbara, USA

D. Barge, R. Bellan, C. Campagnari, M. D'Alfonso, T. Danielson, K. Flowers, P. Geffert, J. Incandela, C. Justus, P. Kalavase, S.A. Koay, D. Kovalskyi, V. Krutelyov, S. Lowette, N. Mccoll, V. Pavlunin, F. Rebassoo, J. Ribnik, J. Richman, R. Rossin, D. Stuart, W. To, J.R. Vlimant

California Institute of Technology, Pasadena, USA

A. Bornheim, J. Bunn, Y. Chen, M. Gataullin, D. Kcira, V. Litvine, Y. Ma, A. Mott, H.B. Newman, C. Rogan, V. Timciuc, P. Traczyk, J. Veverka, R. Wilkinson, Y. Yang, R.Y. Zhu

Carnegie Mellon University, Pittsburgh, USA

B. Akgun, R. Carroll, T. Ferguson, Y. Iiyama, D.W. Jang, S.Y. Jun, Y.F. Liu, M. Paulini, J. Russ, N. Terentyev, H. Vogel, I. Vorobiev

University of Colorado at Boulder, Boulder, USA

J.P. Cumalat, M.E. Dinardo, B.R. Drell, C.J. Edelmaier, W.T. Ford, A. Gaz, B. Heyburn, E. Luiggi Lopez, U. Nauenberg, J.G. Smith, K. Stenson, K.A. Ulmer, S.R. Wagner, S.L. Zang

Cornell University, Ithaca, USA

L. Agostino, J. Alexander, A. Chatterjee, S. Das, N. Eggert, L.J. Fields, L.K. Gibbons, B. Heltsley, W. Hopkins, A. Khukhunaishvili, B. Kreis, V. Kuznetsov, G. Nicolas Kaufman, J.R. Patterson, D. Puigh, D. Riley, A. Ryd, X. Shi, W. Sun, W.D. Teo, J. Thom, J. Thompson, J. Vaughan, Y. Weng, L. Winstrom, P. Wittich

Fairfield University, Fairfield, USA

A. Biselli, G. Cirino, D. Winn

Fermi National Accelerator Laboratory, Batavia, USA

S. Abdullin, M. Albrow, J. Anderson, G. Apollinari, M. Atac, J.A. Bakken, S. Banerjee, L.A.T. Bauerdick, A. Beretvas, J. Berryhill, P.C. Bhat, I. Bloch, F. Borcharding, K. Burkett, J.N. Butler, V. Chetluru, H.W.K. Cheung, F. Chlebana, S. Cihangir, M. Demarteau, D.P. Eartly, V.D. Elvira, S. Esen, I. Fisk, J. Freeman, Y. Gao, E. Gottschalk, D. Green, K. Gunthoti, O. Gutsche, A. Hahn, J. Hanlon, R.M. Harris, J. Hirschauer, B. Hooberman, E. James, H. Jensen, M. Johnson, U. Joshi, R. Khatiwada, B. Kilminster, B. Klima, K. Kousouris, S. Kunori, S. Kwan, C. Leonidopoulos, P. Limon, R. Lipton, J. Lykken, K. Maeshima, J.M. Marraffino, D. Mason, P. McBride, T. McCauley, T. Miao, K. Mishra, S. Mrenna, Y. Musienko⁴¹, C. Newman-Holmes, V. O'Dell, S. Popescu⁴², R. Pordes, O. Prokofyev, N. Saoulidou, E. Sexton-Kennedy, S. Sharma, A. Soha, W.J. Spalding, L. Spiegel, P. Tan, L. Taylor, S. Tkaczyk, L. Uplegger, E.W. Vaandering, R. Vidal, J. Whitmore, W. Wu, F. Yang, F. Yumiceva, J.C. Yun

University of Florida, Gainesville, USA

D. Acosta, P. Avery, D. Bourilkov, M. Chen, G.P. Di Giovanni, D. Dobur, A. Drozdetskiy, R.D. Field, M. Fisher, Y. Fu, I.K. Furic, J. Gartner, S. Goldberg, B. Kim, S. Klimenko, J. Konigsberg, A. Korytov, A. Kropivnitskaya, T. Kypreos, K. Matchev, G. Mitselmakher, L. Muniz, Y. Pakhotin, C. Prescott, R. Remington, M. Schmitt, B. Scurlock, P. Sellers, N. Skhirtladze, D. Wang, J. Yelton, M. Zakaria

Florida International University, Miami, USA

C. Ceron, V. Gaultney, L. Kramer, L.M. Lebolo, S. Linn, P. Markowitz, G. Martinez, J.L. Rodriguez

Florida State University, Tallahassee, USA

T. Adams, A. Askew, D. Bandurin, J. Bochenek, J. Chen, B. Diamond, S.V. Gleyzer, J. Haas, S. Hagopian, V. Hagopian, M. Jenkins, K.F. Johnson, H. Prosper, L. Quertenmont, S. Sekmen, V. Veeraraghavan

Florida Institute of Technology, Melbourne, USA

M.M. Baarmand, B. Dorney, S. Guragain, M. Hohlmann, H. Kalakhety, R. Ralich, I. Vodopyanov

University of Illinois at Chicago (UIC), Chicago, USA

M.R. Adams, I.M. Anghel, L. Apanasevich, Y. Bai, V.E. Bazterra, R.R. Betts, J. Callner, R. Cavanaugh, C. Dragoiu, E.J. Garcia-Solis, L. Gauthier, C.E. Gerber, D.J. Hofman, S. Khalatyan, F. Lacroix, M. Malek, C. O'Brien, C. Silvestre, A. Smoron, D. Strom, N. Varelas

The University of Iowa, Iowa City, USA

U. Akgun, E.A. Albayrak, B. Bilki, K. Cankocak⁴³, W. Clarida, F. Duru, C.K. Lae, E. McCliment, J.-P. Merlo, H. Mermerkaya, A. Mestvirishvili, A. Moeller, J. Nachtman, C.R. Newsom, E. Norbeck, J. Olson, Y. Onel, F. Ozok, S. Sen, J. Wetzel, T. Yetkin, K. Yi

Johns Hopkins University, Baltimore, USA

B.A. Barnett, B. Blumenfeld, A. Bonato, C. Eskew, D. Fehling, G. Giurgiu, A.V. Gritsan, Z.J. Guo, G. Hu, P. Maksimovic, S. Rappoccio, M. Swartz, N.V. Tran, A. Whitbeck

The University of Kansas, Lawrence, USA

P. Baringer, A. Bean, G. Benelli, O. Grachov, M. Murray, D. Noonan, V. Radicci, S. Sanders, J.S. Wood, V. Zhukova

Kansas State University, Manhattan, USA

T. Bolton, I. Chakaberia, A. Ivanov, M. Makouski, Y. Maravin, S. Shrestha, I. Svintradze, Z. Wan

Lawrence Livermore National Laboratory, Livermore, USA

J. Gronberg, D. Lange, D. Wright

University of Maryland, College Park, USA

A. Baden, M. Boutemur, S.C. Eno, D. Ferencek, J.A. Gomez, N.J. Hadley, R.G. Kellogg, M. Kirn, Y. Lu, A.C. Mignerey, K. Rossato, P. Rumerio, F. Santanastasio, A. Skuja, J. Temple, M.B. Tonjes, S.C. Tonwar, E. Twedt

Massachusetts Institute of Technology, Cambridge, USA

B. Alver, G. Bauer, J. Bendavid, W. Busza, E. Butz, I.A. Cali, M. Chan, V. Dutta, P. Everaerts, G. Gomez Ceballos, M. Goncharov, K.A. Hahn, P. Harris, Y. Kim, M. Klute, Y.-J. Lee, W. Li, C. Loizides, P.D. Luckey, T. Ma, S. Nahn, C. Paus, D. Ralph, C. Roland, G. Roland, M. Rudolph, G.S.F. Stephans, K. Sumorok, K. Sung, E.A. Wenger, S. Xie, M. Yang, Y. Yilmaz, A.S. Yoon, M. Zanetti

University of Minnesota, Minneapolis, USA

P. Cole, S.I. Cooper, P. Cushman, B. Dahmes, A. De Benedetti, P.R. Duerdo, G. Franzoni, J. Haupt, K. Klapoetke, Y. Kubota, J. Mans, V. Rekovic, R. Rusack, M. Sasseville, A. Singovsky

University of Mississippi, University, USA

L.M. Cremaldi, R. Godang, R. Kroeger, L. Perera, R. Rahmat, D.A. Sanders, D. Summers

University of Nebraska-Lincoln, Lincoln, USA

K. Bloom, S. Bose, J. Butt, D.R. Claes, A. Dominguez, M. Eads, J. Keller, T. Kelly, I. Kravchenko, J. Lazo-Flores, C. Lundstedt, H. Malbouisson, S. Malik, G.R. Snow

State University of New York at Buffalo, Buffalo, USA

U. Baur, A. Godshalk, I. Iashvili, S. Jain, A. Kharchilava, A. Kumar, S.P. Shipkowski, K. Smith

Northeastern University, Boston, USA

G. Alverson, E. Barberis, D. Baumgartel, O. Boeriu, M. Chasco, S. Reucroft, J. Swain, D. Wood, J. Zhang

Northwestern University, Evanston, USA

A. Anastassov, A. Kubik, N. Odell, R.A. Ofierzynski, B. Pollack, A. Pozdnyakov, M. Schmitt, S. Stoynev, M. Velasco, S. Won

University of Notre Dame, Notre Dame, USA

L. Antonelli, D. Berry, M. Hildreth, C. Jessop, D.J. Karmgard, J. Kolb, T. Kolberg, K. Lannon, W. Luo, S. Lynch, N. Marinelli, D.M. Morse, T. Pearson, R. Ruchti, J. Slaunwhite, N. Valls, J. Warchol, M. Wayne, J. Ziegler

The Ohio State University, Columbus, USA

B. Bylsma, L.S. Durkin, J. Gu, C. Hill, P. Killewald, K. Kotov, T.Y. Ling, M. Rodenburg, G. Williams

Princeton University, Princeton, USA

N. Adam, E. Berry, P. Elmer, D. Gerbaudo, V. Halyo, P. Hebda, A. Hunt, J. Jones, E. Laird, D. Lopes Pegna, D. Marlow, T. Medvedeva, M. Mooney, J. Olsen, P. Piroué, X. Quan, H. Saka, D. Stickland, C. Tully, J.S. Werner, A. Zuranski

University of Puerto Rico, Mayaguez, USA

J.G. Acosta, X.T. Huang, A. Lopez, H. Mendez, S. Oliveros, J.E. Ramirez Vargas, A. Zatserklyaniy

Purdue University, West Lafayette, USA

E. Alagoz, V.E. Barnes, G. Bolla, L. Borrello, D. Bortoletto, A. Everett, A.F. Garfinkel, Z. Gece, L. Gutay, Z. Hu, M. Jones, O. Koybasi, A.T. Laasanen, N. Leonardo, C. Liu, V. Maroussov, P. Merkel, D.H. Miller, N. Neumeister, I. Shipsey, D. Silvers, A. Svyatkovskiy, H.D. Yoo, J. Zablocki, Y. Zheng

Purdue University Calumet, Hammond, USA

P. Jindal, N. Parashar

Rice University, Houston, USA

C. Boulahouache, V. Cuplov, K.M. Ecklund, F.J.M. Geurts, J.H. Liu, B.P. Padley, R. Redjimi, J. Roberts, J. Zabel

University of Rochester, Rochester, USA

B. Betchart, A. Bodek, Y.S. Chung, R. Covarelli, P. de Barbaro, R. Demina, Y. Eshaq, H. Flacher,

A. Garcia-Bellido, P. Goldenzweig, Y. Gotra, J. Han, A. Harel, D.C. Miner, D. Orbaker, G. Petrillo, D. Vishnevskiy, M. Zielinski

The Rockefeller University, New York, USA

A. Bhatti, R. Ciesielski, L. Demortier, K. Goulianos, G. Lungu, C. Mesropian, M. Yan

Rutgers, the State University of New Jersey, Piscataway, USA

O. Atramentov, A. Barker, D. Duggan, Y. Gershtein, R. Gray, E. Halkiadakis, D. Hidas, D. Hits, A. Lath, S. Panwalkar, R. Patel, A. Richards, K. Rose, S. Schnetzer, S. Somalwar, R. Stone, S. Thomas

University of Tennessee, Knoxville, USA

G. Cerizza, M. Hollingsworth, S. Spanier, Z.C. Yang, A. York

Texas A&M University, College Station, USA

J. Asaadi, R. Eusebi, J. Gilmore, A. Gurrola, T. Kamon, V. Khotilovich, R. Montalvo, C.N. Nguyen, I. Osipenkov, J. Pivarski, A. Safonov, S. Sengupta, A. Tatarinov, D. Toback, M. Weinberger

Texas Tech University, Lubbock, USA

N. Akchurin, C. Bardak, J. Damgov, C. Jeong, K. Kovitanggoon, S.W. Lee, P. Mane, Y. Roh, A. Sill, I. Volobouev, R. Wigmans, E. Yazgan

Vanderbilt University, Nashville, USA

E. Appelt, E. Brownson, D. Engh, C. Florez, W. Gabella, W. Johns, P. Kurt, C. Maguire, A. Melo, P. Sheldon, J. Velkovska

University of Virginia, Charlottesville, USA

M.W. Arenton, M. Balazs, S. Boutle, M. Buehler, S. Conetti, B. Cox, B. Francis, R. Hirosky, A. Ledovskoy, C. Lin, C. Neu, R. Yohay

Wayne State University, Detroit, USA

S. Gollapinni, R. Harr, P.E. Karchin, P. Lamichhane, M. Mattson, C. Milstène, A. Sakharov

University of Wisconsin, Madison, USA

M. Anderson, M. Bachtis, J.N. Bellinger, D. Carlsmith, S. Dasu, J. Efron, L. Gray, K.S. Grogg, M. Grothe, R. Hall-Wilton¹, M. Herndon, P. Klabbers, J. Klukas, A. Lanaro, C. Lazaridis, J. Leonard, R. Loveless, A. Mohapatra, D. Reeder, I. Ross, A. Savin, W.H. Smith, J. Swanson, M. Weinberg

†: Deceased

1: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland

2: Also at Universidade Federal do ABC, Santo Andre, Brazil

3: Also at Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France

4: Also at Suez Canal University, Suez, Egypt

5: Also at Fayoum University, El-Fayoum, Egypt

6: Also at Soltan Institute for Nuclear Studies, Warsaw, Poland

7: Also at Massachusetts Institute of Technology, Cambridge, USA

8: Also at Université de Haute-Alsace, Mulhouse, France

9: Also at Brandenburg University of Technology, Cottbus, Germany

10: Also at Moscow State University, Moscow, Russia

11: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary

12: Also at Eötvös Loránd University, Budapest, Hungary

13: Also at Tata Institute of Fundamental Research - HECR, Mumbai, India

- 14: Also at University of Visva-Bharati, Santiniketan, India
- 15: Also at Facoltà Ingegneria Università di Roma "La Sapienza", Roma, Italy
- 16: Also at Università della Basilicata, Potenza, Italy
- 17: Also at Laboratori Nazionali di Legnaro dell' INFN, Legnaro, Italy
- 18: Also at Università degli studi di Siena, Siena, Italy
- 19: Also at California Institute of Technology, Pasadena, USA
- 20: Also at Faculty of Physics of University of Belgrade, Belgrade, Serbia
- 21: Also at University of California, Los Angeles, Los Angeles, USA
- 22: Also at University of Florida, Gainesville, USA
- 23: Also at Université de Genève, Geneva, Switzerland
- 24: Also at Scuola Normale e Sezione dell' INFN, Pisa, Italy
- 25: Also at INFN Sezione di Roma; Università di Roma "La Sapienza", Roma, Italy
- 26: Also at University of Athens, Athens, Greece
- 27: Also at The University of Kansas, Lawrence, USA
- 28: Also at Institute for Theoretical and Experimental Physics, Moscow, Russia
- 29: Also at Paul Scherrer Institut, Villigen, Switzerland
- 30: Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
- 31: Also at Gaziosmanpasa University, Tokat, Turkey
- 32: Also at Adiyaman University, Adiyaman, Turkey
- 33: Also at Mersin University, Mersin, Turkey
- 34: Also at Izmir Institute of Technology, Izmir, Turkey
- 35: Also at Kafkas University, Kars, Turkey
- 36: Also at Suleyman Demirel University, Isparta, Turkey
- 37: Also at Ege University, Izmir, Turkey
- 38: Also at Rutherford Appleton Laboratory, Didcot, United Kingdom
- 39: Also at INFN Sezione di Perugia; Università di Perugia, Perugia, Italy
- 40: Also at KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary
- 41: Also at Institute for Nuclear Research, Moscow, Russia
- 42: Also at Horia Hulubei National Institute of Physics and Nuclear Engineering (IFIN-HH), Bucharest, Romania
- 43: Also at Istanbul Technical University, Istanbul, Turkey